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Interference Cancellation for Hollow-Core Fiber Reference Cells

Jeremias Seppä, Mikko Merimaa, Albert Manninen, Marco Triches, Jan Hald, and Antti Lassila

Abstract—Doppler-free saturated absorption spectroscopy of gases in hollow-core fiber (HCF)-based cells can be used for realizing new compact, robust, and portable frequency standards. In this paper, methods for cancelling interferences resulting from the optical connections between standard fiber and HCF and other factors such as varying coupling to HCF modes are investigated. Laser power modulation with simultaneous detection of ac and dc signal is used to separate saturated absorption from interferences. In addition, a technique of two piezoelectric stack actuators stretching the fiber at different locations is described. The presented experimental results demonstrate that 99% interference attenuation is readily attainable with the techniques. Frequency comb-referenced measurement of saturated acetylene absorption features near $1.54\ \mu\text{m}$, with fiber length and power modulation, is presented. For comparison, measurements and results of the same acetylene fiber, using a system having pump and probe beams at mutually shifted frequencies, are also given.

Index Terms—Frequency measurement standards, infrared spectra, interference cancellation, measurement techniques, metrology, optical fiber, spectroscopy.

I. INTRODUCTION

SATURATED absorption spectroscopy usually requires beams of light passing through low-pressure gas in opposite directions along the same optical path, enabling observation of the center of the spectral transition without Doppler broadening. Using a hollow-core fiber (HCF)-based gas cell [1], [2] in an all-fiber arrangement improves robustness against optical misalignment, mechanical vibration, and temperature changes.

However, interference arising from interfaces between the optical components can be a severe problem. In traditional free-space optical arrangements for spectroscopy and laser stabilization, interference can be attenuated by dithering the end mirror [3]–[5] or by having the pump and probe light

beams crossing at a small angle instead of following the same optical path, causing also a shift to the measured spectrum. However, with the HCF cell it is not usually possible to reflect light back directly from the end of the cell nor to have the pump and probe beams at an angle. Introducing the light into the HCF at both ends by, e.g., having the HCF spliced between telecom fibers produces optical interfaces that can have high reflectivities and losses. Using, e.g., the end mirror and HCF-based arrangement results in complex interference effects from multiple optical interfaces and possibly also effects due to the mode structure of the fiber.

An alternative to using pump and probe light at the same wavelength is having the two light beams with a mutual frequency shift. This has been successfully used for cancelling majority of the interference effects by shifting the interference of the pump and probe light in the interfaces from dc to, e.g., megahertz range frequencies [1], [2]. Using pump and probe light at different wavelengths leads to a somewhat more complicated system, and in principle, attenuates a different subset of the possible interference effects.

In this paper two different methods to attenuate interference effects in HCF-based systems with an end mirror are investigated. First, a piezo modulation scheme, published in [6], using two piezos modulating both the HCF and the end mirror is shown to greatly reduce the interferences in a carbon dioxide-filled fiber spliced between standard single-mode fibers. Second, a method using laser power modulation and ac/dc detection is shown to be able to differentiate the nonlinear saturated absorption from the linear interference and linear absorption to a high degree in a low-pressure acetylene-filled fiber. The dc component of detector signal is detected in both setups using a digital voltmeter (DVM), and in the latter method the ac component is detected using a lock-in amplifier.

The acetylene-filled fiber component used in the latter experiment was made by Danish Fundamental Metrology (DFM), and has coupling lenses at both ends of the HCF. The laser frequency in the latter experiment is locked to atomic clock via frequency comb [7]. The comb repetition rate is stepped to scan the locked laser frequency.

As a third measurement method, recent results with the same HCF cell, using pump and probe light at different frequencies [8] are shown for comparison.

A. Setup With Two Modulating Piezos

The setup for the experiment, shown in Fig. 1, is partly based on previously designed instrumentation [4] that used a bulk glass reference gas cell instead of hollow-core fiber. It comprises an external cavity diode laser (ECDL),

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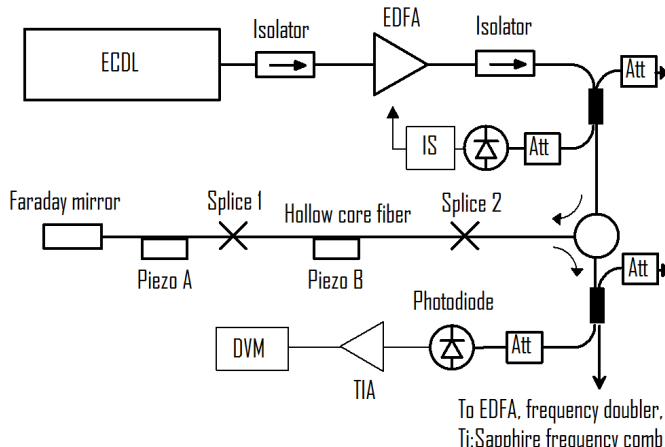


Fig. 1. Measurement setup for feasibility tests using a hollow core fiber gas cell. Att is an attenuator, IS is the intensity stabilizer, and TIA is a transimpedance amplifier.

an erbium-doped fiber amplifier (EDFA), intensity stabilization, HCF, Faraday mirror and circulator, detection, and two piezo stacks. The HCF is an approximately 40-cm long photonic crystal HCF and is spliced to telecom fiber at both ends. In addition to high reflectivity, the splices had high losses. The two piezo stacks, A and B, were glued to the telecom fiber between mirror and splice one, and to the HCF, using a cyanoacrylate glue. The outer protective layers of the telecom fiber were removed before gluing to facilitate stretching.

Piezo A and piezo B were driven by two separate, synchronized signal generators. A triangular waveform at 50 Hz was used for modulating the piezos. This frequency is the local mains frequency and is effectively averaged out by the DVM. Such a low frequency also resulted in good relative sharpness of the turning points of the motion of the piezos. Generally, a more robust choice would have been using a frequency different from the mains frequency with a suitable DVM time constant. However, the system was operable at similar performance level also with, e.g., a 60-Hz piezo modulation.

By looking at the interference fringes in the detected signal with an oscilloscope, the amplitudes were tuned in such a way that each piezo oscillated over an integer number of interference fringes and the relative phase of the signals was tuned in such a way that the piezos changed direction simultaneously. Therefore, the part of the interference effects dependent on the combined stretching effect of both piezos also spread over an integer number of fringe periods. In this experiment piezo A was modulated over a few fringes and piezo B was modulated over a single fringe period. Therefore, the fringe frequencies were also different, helping to further spread the combined interference effects evenly for averaging.

The DVM was used in dc mode and averaging time was 200 ms, effectively averaging the 50-Hz modulation. Stepping of the ECDL wavelength setting was done at 1-s intervals.

B. Setup With Laser Power Modulation

The setup with laser power modulation and frequency comb locking is shown in Fig. 2. The acetylene-filled

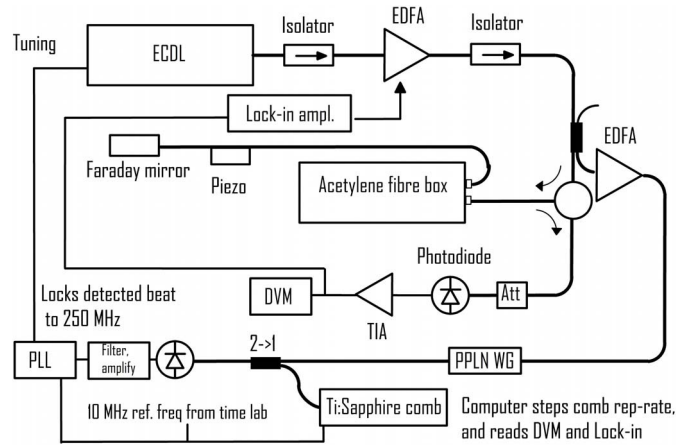


Fig. 2. Measurement setup using low-pressure acetylene-filled hollow core fiber gas cell and laser power modulation. Att is the attenuator, and TIA is the transimpedance amplifier. PLL is phase-locked loop electronics and PPLN WG is periodically poled lithium niobate waveguide.

fiber is situated inside the box denoted as acetylene fiber box. The box has Ferrule Connector/Angled Physical Contact connectors and connecting telecom fibers. The HCF used is a seven-cell photonic crystal fiber with a core diameter of 8 μm and a length of 2.8 m. The acetylene filling pressure has been estimated as 12 Pa, but a pressure increase of approx. 15 Pa/month has been observed due to air leak. All the measurements presented here have been performed within six months of filling.

One fiber length modulating piezo was used at the fiber leading to the end mirror to reduce large (approximately 5% amplitude compared with off-spectrum mean intensity) short-period interferences.

A lock-in amplifier (SRS type 830) was used to provide 333-Hz modulation signal to the pump laser of the first EDFA. The resulting power modulation in the EDFA output was approximately 50% of the mean power. The frequency of the lock-in amplifier was selected in such a way that the detection of the lock-in frequency would not detect much undesired signal from the piezo modulation at 50 Hz. The averaging time constant in the lock-in amplifier was 100 ms. The mean power entering the acetylene fiber box was approximately 10 mW. The second EDFA was added to the system to amplify the power fed into the frequency-doubling crystal, periodically poled lithium niobate waveguide, for higher output power.

The wavelength of the ECDL was tuned close to the measured acetylene transition and then locked to the titanium-sapphire frequency comb via the frequency doubling and using phase-locked loop-type electronics [4]. The wavelength scan was done by stepping the pulse repetition rate of the frequency comb system.

C. Setup With Two Different Wavelengths and Pump Power Modulation

The setup with two different wavelengths for the pump and probe beam is shown Fig. 3. The light provided by the fiber laser (NKT Photonics E15) is split in a 50/50 fiber-splitter. Two acousto-optic modulators (AOMs) are used to blue-shift the light respectively 40 MHz (probe) and

Fig. 6 shows the directly measured dc-coupled detector signal as a function of laser frequency. From scan to scan, the distorted, asymmetric form varied so that the extent and direction of the slant varied. The piezo modulation of the end mirror removed short-period interferences quite effectively but there was still a distorted shape of absorption. To avoid gluing a second piezo to the HCF, an alternative method, i.e., the power modulation scheme, was applied.

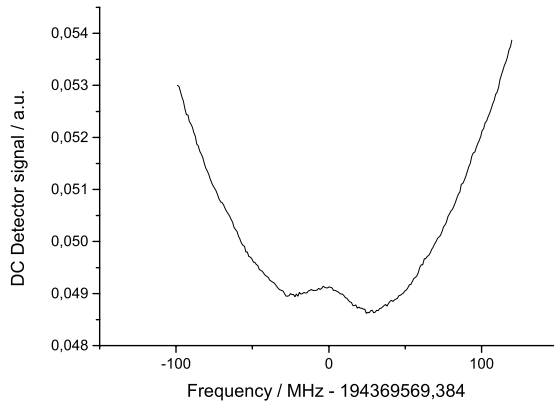


Fig. 6. Recorded dc signal in the scan over the acetylene P16 line.

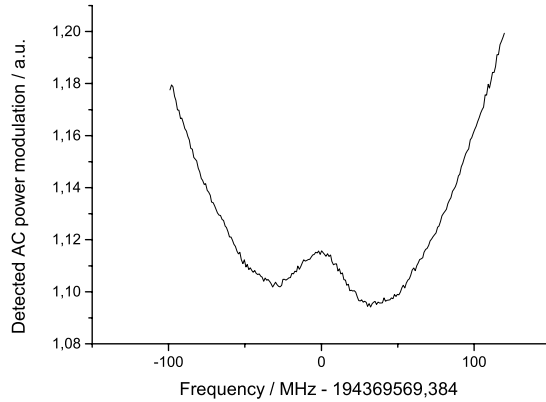


Fig. 7. Recorded ac signal in the scan over the acetylene P16 line.

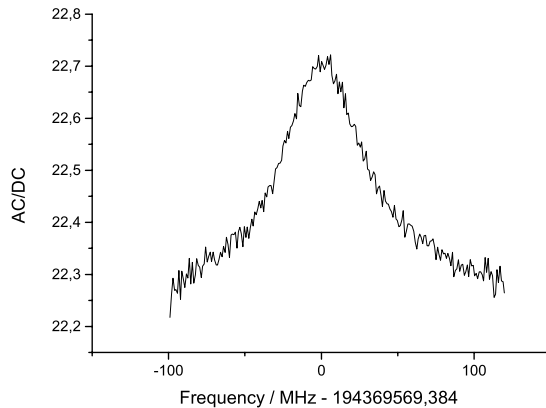


Fig. 8. AC/dc ratio in the scan over the acetylene P16 line.

The comb repetition rate was stepped at approximately 1-s intervals, with approximately 200 measurement points in a single scan. The 1 s wait consisted mainly of waiting for the DVM and lock-in reading to stabilize before reading. All data in Figs. 6–9 are from a single scan.

Fig. 7 shows the ac component detected with the lock-in amplifier simultaneously with the dc component. The Lamb dip is more pronounced due to the nonlinear power response of the saturable medium, although it is still highly distorted.

Fig. 8 shows the ac signal normalized by dividing it by the dc signal. The lamb dip feature is more symmetric, protruding from the Doppler-broadened shape. The ac and dc signals are measured simultaneously from the same scan.

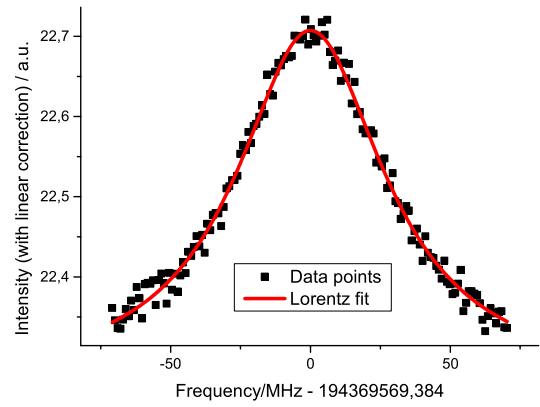
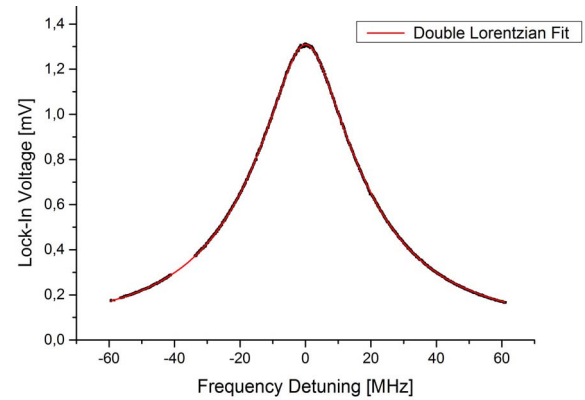


Fig. 9. AC/dc ratio in the central part of the scan over acetylene P16 line with Lorentz fit. A fitted line has been subtracted before the Lorentz fit.

Fig. 10. Lock-in detected sub-Doppler resonance. The data are plotted shifted by 2.5 MHz, because of the different frequency shifts from the two AOMs. The missing of data at -37.5 MHz is due to an instability of a counter reading at a zero-crossing point.

In Fig. 9 the center part is first processed by just subtracting a fitted line to remove the small remaining tilt seen in Fig. 8. Then a Lorentzian function was fitted. The center wavelength of the fit in the figure shown differs from the reference value for low-pressure bulk glass cells only by less than 1 kHz. However, in five repeated experiments, the variation in the fitted central frequency was approximately 200 kHz, and the mean value within 100 KHz of the bulk-cell reference value. The corresponding graphs of the other scans were similar in shape, with slightly changing noise and interference levels probably due to drifting of measurement parameters. The variation of the fitted central frequency is possibly mainly due to the limited number of data points that we were able to measure, compared with the measurement noise level. The majority of the fitted central frequencies were higher than the bulk cell reference value.

C. Comparison With the Two Different Wavelengths Method

Fig. 10 shows the lock-in amplifier output when demodulating the signal acquired by the PD with the external reference frequency (9 kHz). The frequency of the laser is stepped by 100 KHz over a 120-MHz frequency range. Five data points are acquired per frequency step with a lock-in integration time of 100 ms. A delay time of 100 ms has been set

at the beginning of every single step due to the response time of the offset-locking setup. The total acquisition time is about 12 min.

The data in Fig. 10 are fitted with a sum of two Lorentzian functions with individual linewidths and amplitudes but identical center frequencies. This empirical line shape is chosen to include the increased contribution from the slow molecules inside the fiber [1]. At low pressure and low optical power, slow molecules provide a narrow contribution to the signal. The faster molecules have a higher interaction rate with the core wall, destroying the coherence in the light matter interaction and broadening their contribution to the signal. The fit shows a center frequency blue-shifted by approximately 50 kHz. Eight repeated measurements show an average shift of 19 KHz with a standard deviation of 20 kHz. The full-width at half-maximum linewidth is (39 ± 0.4) MHz. The pressure broadening due to the leak of the cell must be considered when compared with the measurements of Figs. 6–9. According to measurements by DFM, the linewidth should be approx. 46 MHz at the time when tests presented in Figs. 6–9 have been performed. The leak-rate observed is under investigation to evaluate the long-term stability of the fiber-filled reference. A complete performance evaluation of the system will be presented in a future work, including a pressure stability characterization.

IV. CONCLUSION

The presented measurement methods provide tools for interference cancellation in HCF-based reference gas cells, and the ac/dc method could also be used to cancel interference in various other saturated absorption measurements. Detection of saturated absorption in HCF cell was shown to be possible without having the pump and probe beams at different frequency. The results suggest that repeatability in the measuring of transition center frequency is possible at least 100 kHz level with acetylene-filled HCF cells, using different measurement techniques.

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Albert Manninen, photograph and biography not available at the time of publication.



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He focused on experimental physics, taking his thesis project abroad, with DTU Nanotech, Kgs. Lyngby, Denmark, during his studies. In the group of Prof O. Hansen, he fabricated and studied the physics beyond the electret-based energy harvester, developing specific silicon micro-fabrication techniques. He currently focuses his research on frequency standard technology with Danish Metrology Institute, Kgs. Lyngby, where he is investigating the hollow core photonics crystal fiber application for laser frequency noise reduction in 1 Hz to 100 kHz bandwidth.

Jan Hald, photograph and biography not available at the time of publication.

Antti Lassila, photograph and biography not available at the time of publication.